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Propeller vs. Magnetar Concepts for SGR/AXPs

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Abstract. Two lines of thought exist as to the nature of Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs). On the one hand, Duncan & Thompson (1992) and Thompson & Duncan (1995) propose neutron stars with super-critical ($> 10^{14}$ G) magnetic fields, which spin-down the stars and power the gamma-ray bursts. On the other hand, several authors (van Paradijs, Taam & van den Heuvel 1995; Chatterjee, Hernquist & Narayan 2000; Alpar 2001; Marsden et al. 2001; Menou, Perna & Hernquist 2001) propose neutron stars with typical pulsar magnetic fields ($\sim 10^{12}$ G), which are spun-down by magnetospheric "propeller" torques from fallback or fossil disks in addition to magnetic dipole radiation. We discuss these two concepts in light of various observations.

1. Magnetar & Fallback Accretion Disk Concepts

Magnetars, defined to be neutron stars possessing dipole magnetic fields in excess of the quantum critical value of 4.4×10^{13} Gauss, constitute a proposed class distinct from radio and x-ray pulsars, in which magnetic energy, rather than rotational energy, plays the dominant role in powering emissions. The strong magnetic dipole radiation (MDR) would spin-down magnetars quite rapidly leaving them with spin periods of a few seconds after $\sim10^3$ years. Repetitive soft gamma-ray bursts are interpreted as due to crust cracking events in the neutron star surface, whereas the super busts seen from SGR0525-66 and SGR1900+14 would result from sudden large-scale magnetic reconnection. Problems replicating the estimated ages of SGR/AXPs in this model have led to modeling extra sources of torque on the system, but with the magnetic energy remaining as the dominant power source (Kouveliotou et al. 1999).

Alternatively, the rapid spindown rates, young ages inferred from the SNR ages, long spin periods clustered around 5-10 s, and $\sim 10^{35}$ erg/s x-ray luminosities for SGR/AXPs can all be explained by models involving the propeller effect on inflowing material as the dominant spindown torque. This material comes from a small accretion disk formed around the neutron star very early in its life. Such a disk can form in several ways: from the inner most ejecta material falling back within a few hours of the initial supernova explosion (Michel 1988; Chatterjee et al 2000); from the reversal of slower-moving inner ejecta by the Sedov phase reverse shock relatively soon after the blast wave hits the progenitor winds (Truelove & McKee 1999); or from high velocity neutron stars capturing comoving ejecta (van Paradijs et al. 1995). Only a very small fraction of the

ejecta is needed to form a fossil disk of $10^{-6}M_\odot$ which is all that is required to explain the spindown of SGR/AXPs via the propeller mechanism. In this model, the exceedingly rapid spindown causes crust cracking and subduction to provide both the energy and mechanism for the very energetic bursts.

2. Observational Constraints

Observations of SGRs and AXPs have revealed many of the characteristics of these objects that must be explained by a successful theory (Rothschild, Marsden & Lingenfelter 2002). Additionally, the theory must predict or be consistent with ideas of the histories of such objects, such as conditions surrounding their birth and their galactic inventory. Table 1 gives a list of constraints and whether or not they are explained by either of the two concepts for SGR/AXPs. We discuss each of these constraints below.

Table 1. Observational Constraints

Constraint	Value	Magnetars	Disks
Spin Period Distribution	Clustered around 5-10 s	No	Yes
Spin-Down Rates & Ages	P/2$\dot{P} \neq$ SNR Age	No	Yes
Braking Indices	$\neq$3	No	Yes
Spin-Down Noise	Larger than in Pulsars	??	Yes
Located in Dense ISM	Opposite than for Pulsars	No	Yes
Visibility of Accretion Disk	Very small if at all	Yes	??
Number of Objects	$\sim$10	??	Yes
Normal Burst Energy	$\sim 10^{41}$ergs	Yes	Yes
Super Burst Energy	$\sim 10^{44}$ergs	Yes	Yes
Burst Durations	$\sim$ 0.2s	Yes	Yes
Abrupt Changes in $\dot{P}$	$\Delta\dot{P}/P \approx$1	No	Yes
Change in Pulse Profile	Simplified at Superburst	Yes	??

A basic property of AXP/SGRs is their narrow range of spin periods from 5 to 10 s. Such a clustering is a natural result of the equilibrium period reached by the propeller effect in low luminosity accretion disks around neutron stars with the pulsar distribution of magnetic fields, but is not consistent with the magnetars, which should show a much wider range of values, even with field decay.

Another basic property of the AXP/SGRs is their measured spin-down rates and periods, which give MDR spin-down ages ($P/2\dot{P}$) expected in the magnetar model that are much shorter and not consistent with the ages of the associated supernova remnants. Therefore, another source of torque on the neutron star must be present in the magnetar model. Addition of propeller driven spin-down can give ages that are quite consistent with the associated supernova remnants. The original magnetar model has been modified to include a torque component from a relativistic wind in order to correct age predictions. But such a wind must have nearly a 100% efficiency for x-ray production, to be consistent with the quiescent flux and still require super-critical magnetic fields. Rothschild, Marsden & Lingenfelter (2000) have shown that an x-ray production efficiency

of a few percent or less for the wind implies sub-critical fields consistent with typical pulsar values. The measured Ps and $\dot{P}$s of the SGRs together with their ages also give braking indices which are significantly different than the value of 3, predicted for MDR alone, but are quit consistent with that expected from propeller driven spin-down.

The timing noise in AXP/SGRs is much larger than that found in radio pulsars from MDR, although additional mechanisms have been proposed by Thompson et al. (2000) that might account for such noise for magnetars. The timing noise is comparable to that seen in accreting binary x-ray pulsars (Woods et al. 2000), as would also be expected from variable accretion in the propeller model.

Most, if not all, of the AXP/SGRs are associated with known supernova remnants to a high degree of statistical significance (Marsden et al. 2001; see Gaensler et al. 2001 for a contrary opinion). One can use these SNRs to probe the density of the environment in which the AXP/SGRs were born. While 80-90% of neutron star-producing core-collapse SNae occur in the hot tenuous medium of superbubbles, the SNae associated with AXPs and SGRs show the opposite tendency, i.e., >80% occur in the denser ISM. Such higher densities will confine the massive progenitor winds much closer to the star and these will decelerate the blast wave much more rapidly and initiate the reverse shock in the remnant (Truelove & McKee 1999). This can create the fallback disks to spin-down the neutron star to the narrow, 5-10 s period range. Thus, the fallback disk accretion model naturally explains high ISM density at the birth sites. Nothing in the magnetar model requires, or explains why the ambient density need be any different than that for neutron stars in general.

The dense ISM accretion models predict that a dozen AXP/SGRs have been formed in the last 20 kyrs, assuming 20% as the fraction of new neutron stars born in dense ISM, 10% for the fraction of massive, rapidly evolving progenitors that experience mass loss sufficient to form a pushback disk in dense ISM environments (Marsden et al. 2001), and a SNae rate of 1/40 yr^{-1} over the last 20 kyr. Thus, the fallback disk scenario can successfully predict the numbers seen. The magnetar model provides no such estimate.

High sensitivity optical observations of particular SGR/AXPs have set strong limits on the size of accretion disks assuming the standard disk model (e.g. Kaplan et al. 2001; Hulleman et al. 2000). However, Menou et al. (2001) have modeled the dusty, metal-rich disks expected from supernova fallback and they find that these upper limits are consistent with such disks. Observations in the infrared are required to test for the presence of such disks that will cool by very different means than the standard hydrogen/helium alpha disks.

The total energy of SGR bursts amount to about 10^{44} ergs for the rare super bursts and about 10^{41} ergs for the weaker more frequent bursts. In the propeller model, it is proposed that the rapid spin down of the star creates dynamical stresses within the crust to produce frequent crustal quakes that provide the energy for the weaker bursts, while rarer, much stronger quakes from compressive phase changes in subducted crust can provide the energy for the super bursts. Vibrations excited by these quakes will be transmitted into magnetospheric Alvèn waves which accelerate particles, producing the x-ray/gamma-ray emission. In the magnetar model, it is proposed that the weaker frequent bursts

are also caused by quakes, but ones resulting from crustal cracking produced by magnetar fields. The rarer super bursts come from magnetic reconnection.

The short durations, typically about 0.2 s, of most of the weaker bursts, as well as the impulsive phase of the super bursts, have been attributed to either the gravitational radiation damping time of neutron star vibrations (Ramaty, Bussard & Lingenfelter 1980) which provide an extended energy source in subcritical field models, or the storage time for energy in the neutron star crust (Blaes et al. 1989) for a much briefer energy input in the magnetar model. Assuming nearly instantaneous injection of all of the super burst energy into a pair plasma in the magnetar model, a superstrong magnetic field would be required in order to contain that energy. In subcritical field models, where the both the spectral hardness and luminosity of super bursts can be explained (Ramaty et al. 1981; Lindblom & Detweiler 1983) by synchrotron emission in $\sim 10^{12}$ G fields, most of the energy is stored in the neutron star vibrational modes so that the energy in the radiating pair plasma can easily be confined by the $\sim 10^{12}$ G field.

The spin-down rate of SGR 1900+14 measured after the super burst on August 27, 2000, increased by a factor of 2 over that prior to the burst. Such an increase would imply an increase in magnetic field energy in a magnetar, which is just the opposite of what would be expected if the burst were powered by magnetic reconnection which should reduce the field. For the propeller model, assuming a "standard" hydrogen disk, Thompson et al. (2000) suggested that the burst would have disrupted the inner portions of an accretion disk, reducing spin-down. But a thin, high metallicity fallback disk could easily survive the burst, because the total energy deposited in the disk would be much less than its gravitational binding energy, and heating of the inner edge of the disk can temporarily increase the propeller torques, as is observed.

3. Conclusions

The success of the accretion models is that they require only the well-studied properties of neutron stars and supernovae, and they can be applied beyond AXP/SGRs to clarify contradictions in interpretations of other neutron stars. These models predict the non-bursting attributes — luminosity, spin period, spin-down rate — as well as the low number seen in the Galaxy. Spin-down driven quakes can also power both the repetitive bursting and the super bursts, and the durations of these bursts are consistent with postquake vibrational damping times. Direct observations of the disks, however, are needed to establish their existence.

The magnetar model with relativistic winds can also explain both the persistent and bursting x- and gamma-ray emission from SGRs, and the spin-down of both the SGRs and AXPs, if the wind x-ray emission efficiency is near 100%. The magnetar model, however, does not explain the clustering of spin periods observed in these sources, even with magnetic field decay. Theoretical arguments suggest that magnetic fields can exist far above the critical field, but observational evidence from all of the radio pulsars, whose implied fields from P and $\dot{P}$ span over 5 orders of magnitude, show a clear cutoff just short of the critical field.

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